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Spectrum of cosmic rays, produced in supernova remnants

E.G. BEREZHKO[1], H.J.VÖLK[2]
[1]*Yu.G. Shafer Institute of Cosmophysical Research and Aeronomy, 31 Lenin Ave., 677980 Yakutsk, Russia*
[2]*Max Planck Institut für Kernphysik, Postfach 103980, D-69029 Heidelberg, Germany*
berezhko@ikfia.ysn.ru

Abstract: Nonlinear kinetic theory of cosmic ray (CR) acceleration in supernova remnants (SNRs) is employed to calculate CR spectra. The magnetic field in SNRs is assumed to be significantly amplified by the efficiently accelerating nuclear CR component. It is shown that the calculated CR spectra agree in a satisfactory way with the existing measurements up to the energy 10^{17} eV and that this component plus a suitably chosen extragalactic CR component can give a consistent description for the entire Galactic CR spectrum.

Introduction

Supernovae (SN) have enough power to drive the Galactic cosmic ray (GCR) acceleration. The only theory of particle acceleration which at present is sufficiently well developed and specific to allow quantitative model calculations is diffusive acceleration applied to the strong outer shock associated with SNRs. Considerable efforts have been made during the last years to empirically confirm the theoretical expectation that the main part of GCRs indeed originates in SNRs. Theoretically, progress in the solution of this problem has been due to the development of a kinetic nonlinear theory of diffusive shock acceleration (e.g. [1, 2]). This theory attempts to include all the most relevant physical factors, essential for the evolution and CR acceleration in a SNR. The application of the theory to individual SNRs and their known synchrotron emission [3, 2, 4] has demonstrated its capability of explaining the observed SNR properties and in calculating new effects like the extent of magnetic field amplification.

Here we apply kinetic nonlinear theory assuming a time-dependent amplified magnetic field, consistent with multi-wavelength evidence from individual objects, in order to approximately calculate the spectra of CRs produced in Galactic SNRs. It is shown that these spectra are approximately consistent with the existing measurements of GCR spectra up to an energy of 10^{17} eV.

Model

Our nonlinear model is based on a fully time-dependent solution of the CR transport equation together with the gas dynamic equations in spherical symmetry (e.g. [1]). SN explosion ejects an expanding shell of matter into the surrounding ISM. Due to the streaming instability CRs efficiently excite large-amplitude magnetic fluctuations upstream of the SN shock. Since these fluctuations scatter CRs extremely strongly, the CR diffusion coefficient is as small as the Bohm limit. The modeling of magnetic field evolution [5, 6] concluded that a considerable amplification to what we call an effective magnetic field $B_0 \gg B_{ISM}$ should occur, where B_{ISM} is the preexisting field in the surrounding ISM. The Bohm limit is then expected to refer to this amplified field.

From an analysis of the synchrotron spectrum of young SNRs [2] such a strong magnetic field amplification can only be produced as a nonlinear effect by a very efficiently accelerated nuclear CR component. In fact, for all the thoroughly studied young SNRs, the ratio of magnetic field energy density $B_0^2/8\pi$ in the upstream region of the shock precursor to the CR pressure P_c is about the same [3]: $B_0^2/(8\pi P_c) \approx 5 \times 10^{-3}$.

The number of suprathermal protons injected into the acceleration process is described by a dimensionless injection parameter η which is a fixed fraction of the number of ISM particles entering the shock front. We adopt here a value $\eta \sim 10^{-4}$, which is consistent with the theoretical expectation and which is close to the values determined individually for young SNRs [2]. We use the injection rate of ions heavier than protons which provide ion-to-proton ratios as observed in the GCRs at an energy of 1 TeV. The physical factors (ion injection rate and acceleration efficiency) which determine this ratio were discussed by [7].

The overall CR spectrum $N(\epsilon, T_{SN})$ is formed during the active period of SNR evolution which lasts up to the time T_{SN} when the SN shock becomes too weak to accelerate efficiently a new portion of freshly injected particles. After their release from the parent SNRs the accelerated CRs occupy the confinement volume more or less uniformly with an intensity $J(\epsilon) \propto \tau_{esc}(R)N(\epsilon)$ where $\tau_{esc}(R)$ is the mean residence time, $R = pc/(Ze)$ is rigidity, p is momentum, $\epsilon = Amc^2 + \epsilon_k$ and ϵ_k are total and kinetic particle energy respectively.

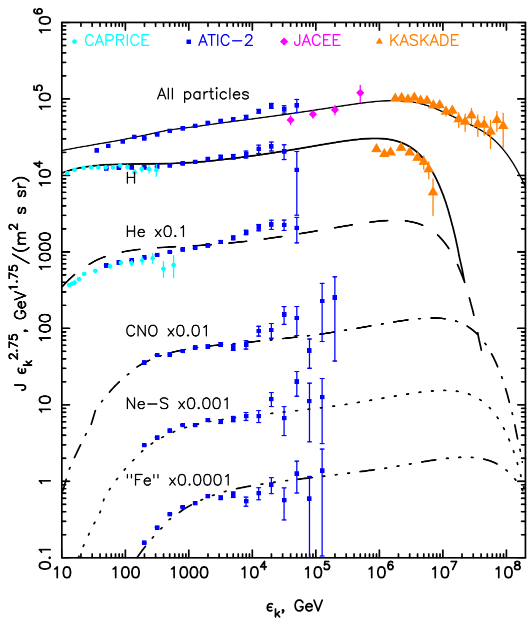

Figure 1: GCR intensities at the Solar system as a function of kinetic energy. Experimental data obtained in the CAPRICE [8], ATIC-2 [9], JACEE [10] and KASCADE [11] experiments are shown as well.

Results and Discussion

We use the values $E_{\rm SN} = 10^{51}$ erg for the explosion energy and $M_{\rm ej} = 1.4 M_\odot$ for the ejecta mass which are typical for SNe Ia in a uniform ISM. The active phase of the average SNR as CR source was assumed to last until an age of $T_{SN} \approx 10^5$ yr.

In Fig.1 we present the calculated intensities $J(\epsilon) \times \epsilon^{2.75}$ of protons (H), Helium, three groups of heavier nuclei, and "All particles" as a function of kinetic energy. Here we have used $\tau_{esc} \propto R^{-\mu}$, with $\mu = 0.75$. The results of the recent experiments CAPRICE, ATIC-2 , JACEE and KASCADE, which in our view are the most reliable, agree quite well with this theoretical calculation up to the energy $\epsilon_k \approx 10^{17}$ eV. One can see that the theory fits the existing data in a satisfactory way up to the energy $\epsilon_k \approx 10^{17}$ eV. The main exception is the Helium spectrum as measured in the recent ATIC-2 balloon experiment which is noticeably harder than the proton spectrum, in contrast to the theoretical expectation.

The second difficulty for the present theory are the calculated very hard *overall* CR source spectra which, say for protons, have the form $N \propto \epsilon_k^{-1.9}$ for $\epsilon_k < 10^{15}$ eV. This spectrum is noticeably harder than the source spectrum $N \propto \epsilon_k^{-2.1}$, deduced in the framework of our preferred CR propagation model which includes a selfconsistent halo within a Galactic wind [12]. However, it was argued [13] that already in the middle Sedov phase nonlinear dissipation will increasingly reduce the field amplification and particle scattering below the Bohm limit. High-energy particles will then increasingly leave the SNR which can only continue to accelerate lower and lower energy particles. Although there is a need for a more detailed analysis of this effect, it should lead to some softening of the overall GCR spectrum as the result of escape at high and continued acceleration at lower energies in older SNRs.

According to Fig.1 the knee in the observed all-particle GCR spectrum has to be attributed to the maximum energy of protons, produced in SNRs. The steepening of the all particle GCR spectrum above the knee energy 3×10^{15} eV is a result of the progressively decreasing contribution of light CR nuclei with increasing energy. Such a scenario is confirmed by the KASCADE experiment which shows relatively sharp cutoffs of the spectra of various GCR species at energies $\epsilon_{max} \approx 3Z \times 10^{15}$ eV [11], so that at energy $\epsilon \sim 10^{17}$ eV the GCR spectrum is expected to be dominated by the contribution from the iron nuclei.

In Fig.2 we present an all-particle spectrum which includes two components: (i) CRs produced in SNRs and (ii) extragalactic CRs, protons plus 10% Helium, presumably produced in Active Galactic Nuclei [14]. The second component has been chosen to have a power-law source spectrum $J_s \propto \epsilon^{-2.7}$ above an energy $\epsilon \sim 10^{16}$ eV up to energies in excess of 10^{20} eV.

Compared with the source spectrum $J_s(\epsilon)$ the component $J(\epsilon)$, observed in the Galaxy, is modified by two factors. At energies $\epsilon > 10^{18}$ eV the shape of $J(\epsilon)$ is influenced by the energy losses of CRs in intergalactic space as a result of their interaction with the cosmic microwave background that leads to the formation of a ”dip” structure at $\epsilon \sim 10^{19}$ eV, and to a GZK-cutoff for $\epsilon > 3 \times 10^{19}$ eV [14].

At $\epsilon < 10^{18}$ eV the spectrum $J(\epsilon)$ is determined by the character of CR propagation in intergalactic space, followed by adiabatic cooling [14]. CRs penetrating into the Galaxy from outside are in addition subject to modulation by the Galactic wind. We describe this effect by the modulation factor $f = \exp(-\epsilon_{\rm m}/\epsilon)$, where $\epsilon_{\rm m} = 10^{17}$ eV [18].

Cf. [14], presenting data of the AGASA, Yakutsk and HiRes detectors in Fig.2, we shift the energies by a factor of $\lambda = 0.9$, 0.85 and 1.2 respectively, so that the measured CR fluxes agree with each other.

According to Fig.2 the calculated GCR spectrum is in reasonable agreement with the existing data. It leads us to the following conclusion: if the observed CR spectrum at energies $\epsilon > 10^{18}$ eV is indeed dominated by the contribution from extragalactic sources [the so-called ”dip-model” of [14]], then we do not need any other Galactic source population except SNRs, as calculated above. However, if the extragalactic sources produce in reality a much harder spectrum $J_s \propto \epsilon^{-2}$ (the so-called ”ankle-model”) then their contribution becomes dominant only at energies $\epsilon > 10^{19}$ eV. Therefore, to fit the observed GCR spectrum an additional Galactic source population is required whose contribution is essential in the energy range $10^{17} < \epsilon < 10^{19}$ eV. It could possibly result from CR reacceleration processes [7], for example, in the interaction regions of the Galactic Wind induced by the spiral structure in the Galactic Disk [18].

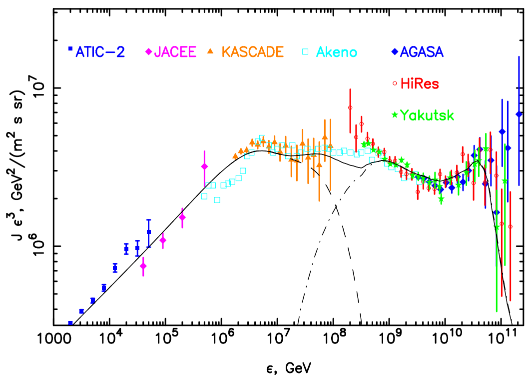

Figure 2: All-particle GCR intensity as a function of total particle energy. The dashed and dash-dotted lines represent the Galactic component, which is the all-particle spectrum from Fig.1, and the extragalactic component respectively. Experimental data obtained in the ATIC-2, JACEE, KASCADE, Akeno - AGASA [15], HiRes [16] and Yakutsk [17] experiments are shown as well.

We note that these two scenarios for the extragalactic component predict a very different CR chemical composition above about 3×10^{17} eV. Since within the range $3Z \times 10^{15} < \epsilon < Z \times 10^{17}$ eV reacceleration produces a power law tail of the CR spectrum originally produced in SNRs, it is clear that the observed CR spectrum is expected to be dominated by the iron contribution at energies $10^{17} < \epsilon < 10^{19}$ eV. It is very much different from what is expected within the dip-model.

In order to illustrate the CR chemical composition, expected in the latter case, we present in Fig.3 the mean logarithm of the GCR atomic number. At en-

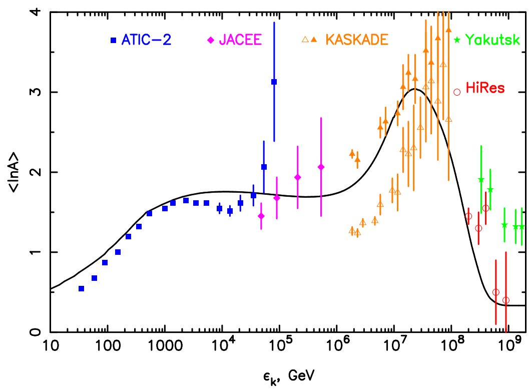

Figure 3: Mean logarithm of the CR nucleus atomic number as a function of kinetic energy. Experimental data obtained in the ATIC-2, JACEE, KASCADE [19], HiRes [20] and Yakutsk [21] experiments are shown as well.

ergies $\epsilon < 1$ TeV $A(\epsilon)$ increases with energy and for $10^3 < \epsilon < 10^6$ GeV we have $< \ln A > \approx 6$. Due to the dependence of the maximum energy of CRs produced in SNRs, $\epsilon_{max} \propto Z$, on the charge number Z and therefore on A, CRs become progressively heavier above the proton cutoff energy $\epsilon \approx 3 \times 10^{15}$ eV. The mean atomic number of the CRs produced in SNRs goes towards the value $A = 56$ as the energy approaches 10^{17} eV. However, already at $\epsilon > 10^{16}$ eV the contribution of extragalactic CRs becomes essential. Therefore $< \ln A >$ reaches its peak value at $\epsilon \approx 2 \times 10^{16}$ eV and then diminishes with increasing energy to the value $0.1 \ln 4$.

The calculated atomic number agrees reasonably well with the existing data up to a particle energy of $\epsilon \sim 10^{16}$ eV. At higher energies $A(\epsilon)$ goes down with energy similar to the Yakutsk [21] and HiRes data. Quantitatively the calculated value of $< \ln A >$ agrees well with the HiRes data. Since the existing data demonstrate that above 10^{17} eV CRs become lighter with energy, this could be considered to favor the dip-scenario.

We conclude that the expected GCR spectrum, produced in SNRs, fits the existing GCR data in a satisfactory way up to the energy 10^{17} eV.

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